MSV SIGNAL PROCESSING SYSTEM FOR NEUTRON-GAMMA DISCRIMINATION IN A MIXED FIELD

by

Srboljub J. STANKOVIĆ [1]***, Bratislav D. IRIČANIN*** [2]***, Dragana NIKOLIĆ*** [1]***, Ksenija S. JANKOVIĆ*** [3]***, Mirjana RADENKOVIĆ*** [1]***, Koviljka Dj. STANKOVIĆ*** [2]***, and Predrag V. OSMOKROVIĆ*** [2]

[1] Vinča Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[2] Faculty of Electrical Engineering, University of Belgrade, Belgrade, Serbia
[3] Institute for Testing Materials – IMS, Belgrade, Serbia

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Based on the principles derived from Campbell's theorem, this paper carries out an analysis of the possibilities of Campbell's mean square value signal processing system. The mean square value mode is especially suitable for measurements performed in a mixed radiation field, because the quantities of electrical charge involved in the interactions of the two types of radiation are substantially different. The measuring detector element may be an adequate ionization chamber and/or semiconductor components for mixed n-γ fields. An examination of the discrimination of gamma in relation to the neutron component in the signal of the detector output was carried out, calculated according to the theoretical model of radiation interaction with the detector. The advantage of the mean square value method was confirmed and it was concluded that the order of n-γ discrimination in mean square value signal processing is greater than the one rendered by the classical measuring method.

Key words: neutron-gamma discrimination, ionization chamber, semiconductor detector

INTRODUCTION

Previous and existent modes of detector signal processing systems in mixed, neutron plus gamma fields, have taken the form of steady-state ionization current operations, pulse rate modes and, more recently, the so-called Campbeling technique of operation. A modern detector signal processing system in a mixed field has a combination of components such as PIN diodes, MOSFETs and/or ionization chambers. The PIN diode is an n-type silicon crystal with a surface area with a p-type layer wrapping, doped with boron atoms [1]. Fast neutrons are detected via recoiled protons that emerge from the epoxy resin around the PIN diode. Thermal and intermediate neutrons are detected via alpha and ^{7}Li particles from the ^{10}B(n, a)^{7}Li reactions in the n-layer implanted with the boron atoms. Low energy photons are mainly detected via photoelectric and Compton interactions inside the depleted region, while higher energy photons are also detected via their Compton interactions with the depletion region or surrounding materials. The amplification system coupled to the detector is composed of a charge-sensitive preamplifier and a main amplifier and single channel analyzers which discriminate pulse heights corresponding to deposited energies of neutrons and photons. The discriminator has three separate channels: fast neutron and thermal neutron channels and a photon channel. The pulse height was analyzed with a multichannel analyzer. PIN diode sensitivity, dV_f /dD_n, where V_f is the forward voltage on the PIN diode, and D_n is the fast neutron dose, is practically constant over the entire dose range of 0.01-100 Gy [2]. The response of MOSFET dosimeters (RadFET) to different particle environments is under investigation at CERN (European Organization for Nuclear Research) the aim being the application of this radiation monitoring technology to the compact muon solenoid (CMS) experiment and also, possibly, to other large hadron collider (LHC) experiments. It was found that, at high neutron fluencies, significantly different sensitivities and strong saturation effects in RadFET responses due to different gate oxides can arise [3]. MOSFET sensitivity to gamma irradiation is dV_{th}/dD_g, where V_{th} is the threshold voltage shift of MOSFET, and D_g is the gamma dose. A semiconductor high-level dosimetry system (SHLD) was part of the Stanford Linear Accelerator Center (SLAC) mixed field for measuring photon and neutron doses

* Corresponding author; e-mail: srbas@vinca.rs

around the copper beam dump. The SHLD was composed of dual MOSFET, a wide-base PIN diode and a microprocessor-controlled reader. The MOSFET can be used to estimate the photon dose, if the ionizing effects of the neutrons can be excluded. The neutron sensitivity of the PIN diode is approximately of a factor around 2000 times higher than its photon sensitivity. Therefore, the PIN diode can be used to measure the neutron dose, while virtually ignoring the photon dose contribution [4]. Silicon PIN diodes and MOSFET sensors [5, 6] are unique because of their small size which prevents the distortion of the radiation field at the measurement point. They can be used for the verification of dose plans in neutron and megavoltage X-ray therapy. Among the early successful realizations of Campbell's theorem in the praxis of nuclear engineering and ionizing radiation protection was Lichtenstein's patented instrument for the measurement of radiation from 1959 [7]. The next step on the road of development in the field was the pulsed ion chamber mode of operation. This operation mode was demonstrated in the gamma-compensated pulsed-ionization chamber wide range neutron measurement system on reactor power [8]. Since 1960, the mean square value (MSV) method has been thoroughly verified and recommended for monitoring reactor start-up power [9, 10]. The MSV (Campbell's) method is used in the in-core monitoring system of reactor power, in a rather large intermediate power range (6-7 decades). Thereby, field gamma components mask the neutron signal less and the effects of ionization chamber current leakage at high reactor core temperatures are eliminated [11-14]. Upon observing the history and application of Campbell's method, Knoll [15] highlighted its significance in radiation protection and dosimetry.

THEORY

The MSV mode is especially suitable for measurements performed in a mixed radiation field, because quantities of electrical charge involved in interactions of the two types of radiation are substantially different. Occasionally, when the classic current mode is used, the direct current measured depends on partial contribution, regardless of the existent radiation type. In MSV mode, linear dependence appears for square quantity of electrical charge per event for each radiation type apart. Therefore, the MSV mode favors the radiation type which yields to detector response with a larger average electrical charge per interaction event (q_1). Essentially, it fulfils better discrimination for one of the radiation field components. It is important to notice that the undesirable component contribution in the output signal of a measured chain is "repressed", and this represents discrimination in the broadest sense. This property of the MSV mode is utilized on an uncompensated ionizing BF_3 chamber as a neutron detector for the increment yield of the signal component which results from the neutron in relation to the yield of the gamma component with less q_1. The MSV mode is most frequently used in the intermediate reactor power range. In special cases, the detector output signal which depends on the flux of neutrons can be used through the appropriate system for processing signals simultaneously in three modes: pulse, MSV, and current mode [16, 17]. When conducting measurements with ionization chamber outside the core (out-of-core), it was determined that the uncorrelated noise as a radnom variable contributes by its fluctuations to the spectral power density of neutron flux [18-21]. A highly uncorrelated gamma field of the output of such an ionization chamber could be defined for both of the measured systems by the relative ratio of the contributions in the output signal originating from neutron and gamma radiation, via a measured variable:

– for the standard method of measuring the direct current of the ionization chamber

$$O_{\mathrm{DC}} \quad \frac{s_{\mathrm{n}} \overline{q}_{\mathrm{n}} \phi_{\mathrm{n}}}{s_{\gamma} \overline{q}_{\gamma} \dot{X}} \tag{1}$$

where, $s_{\mathrm{n}} q_{\mathrm{n}}$, $s \, \overline{q}$ are modified detector susceptibility (ionization chamber) at neutron (in A/nV) and gamma radiation [A/(C/kgs)], respectively; φ_{n}, φ are the neutron and gamma flux [neutrons/cm^{2}s and photons/cm^{2}s]; $\dot{X}(\varphi_{\gamma})$ is the exposure dose [C/kgs]:

– for Campbell's method of measuring current variance

$$O_{\mathrm{AC}} \quad \frac{s_{\mathrm{n}} \overline{q_n^2} \phi_{\mathrm{n}}}{s_{\gamma} \overline{q_{\gamma}^2} \dot{X}} \tag{2}$$

Now, inasmuch as ratios, for $O_{\mathrm{AC}}/O_{\mathrm{DC}}$ we have obtained

$$\frac{O_{AC}}{O_{DC}} \quad \frac{\overline{q_n^2} / \overline{q_{\gamma}^2}}{\overline{q}_{\mathrm{n}} / \overline{q}_{\gamma}} \quad \frac{\overline{q_n^2}}{\overline{q_n}^2} \frac{\overline{q_{\gamma}^2}}{\overline{q_{\gamma}}^2} \quad \frac{\overline{q_{\mathrm{n}}}}{\overline{q_{\gamma}}} \quad \frac{\overline{q_{\mathrm{n}}}}{\overline{q_{\gamma}}} \tag{3}$$

Relation (3) suggests the use of Campbell's measuring method for reactor power monitoring because of better neutron-gamma discrimination. In reactor engineering, the repressing of the undesirable gamma component contribution to the output signal against neutron radiation contribution is conventionally adopted as neutron-gamma discrimination. The improvement in discrimination is significant because fission reactor power is proportionate to the neutron flux, *i. e.* the only significant and useful information of reactor power monitoring is the one concerning the neutron flux.

EXPERIMENTS

Significant improvements in discrimination which Campbell's method offers in cases when the ionization chamber is used for the purpose is several orders of magnitude discrimination, namely for factor 10^3 that supervened $\overline{q}_n / \overline{q}_\gamma \quad 10^3$ [12]. This is of special interest for some ionization chamber types which couldn't be gamma compensated when neutron flux determination is concerned. In this paper, the uncompensated out-of-core ionization chamber is observed, although this conclusion is more applicable to the in-core ionization chamber. The main advantage of out-of-core ionization chambers is the high-grade independence of the output signal value from local spatial changes of neutron flux. An uncompensated ionization chamber, RSN-337, (length (L) = 33 cm, diameter (D) = 8 cm), was set up by the carrier so that its axial axis was at a height (h) of 81 cm above the bottom of the reactor vessel and the axis perpendicular to the axial axis cylinder of the vessel. This means that the base of the reactor chamber outside the vessel leans against the wall of the vessel, so that the ionization chamber is, in relation to the axial symmetric axis of the vessel, set to the BF_3 counter which monitors changes in nuclear reactor power.The BF_3 ionization chamber is followed by a Keithley electrometer with a signal amplifier, AD conversion system and personal computer required for forming the MSV detector signal processing system by using adequate software, as is shown in fig. 1. Code A24 is composed of a modulus for data acquisition from a sequence of converted signal values and a separate modulus for data processing and variance of converted signal computing [22]. In our experiments, the amplifier stage and A/D converter are followed by an electronic element for signal squaring which uses numerical simulation in software code A24. Previously, voltmeters for the mean square signal value or circuit based on the principal of keeping a constant temperature on the thermocouple were used for the purpose [16, 17, 23, 24].

High-quality experimental conditions, values of the thermal neutron flux and absorbed, equivalent and exposure dose rates at the spatial point of interest within mixed fields around the reactor vessel of the HERBE system, realized in the RB reactor at the Vinča Institute of Nuclear Sciences, Belgrade, were determined with sufficient certainty. The values of the thermal neutron flux for the field outside the reactor vessel, in radial and axial direction, were confirmed or determined in an experimental manner by using activation detectors. The estimation of the thermal neutron flux on the reactor vessel wall was done with software code FLRB, created by the NTI Center-150 at the Vinča Institute of Nuclear Sciences. The first set of experiments at the RB nuclear reactor (system HERBE) involved the determination of the signal mean value and variance in stationary rating at fission power levels of 10 mW, 50 mW, 100 mW, and 1 W. During measurement, the direct current range was 10^{-3} A. The first important conclusions on the advantage of MSV over the classic monitoring method of fission power are shown in figs. 2 and 3. When the interval of fission power changes from 10 mW to 1 W, successive ratios have been obtained

$$\frac{\Delta \log V}{\Delta \log \dfrac{P}{P_0}} \quad 1.15$$

$$\frac{\Delta \log (\mathrm{var} V)}{\Delta \log \dfrac{P}{P_0}} \quad 0.94; \; P_0 \quad 1\,\mathrm{W} \tag{4}$$

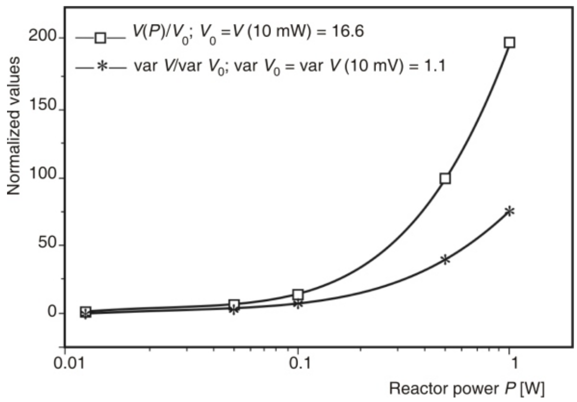

Figure 2. Determination of signal mean value and variance in stationary rating at fission power levels of 10 mW, 50 mW, 100 mW, and 1 W by using the standard method

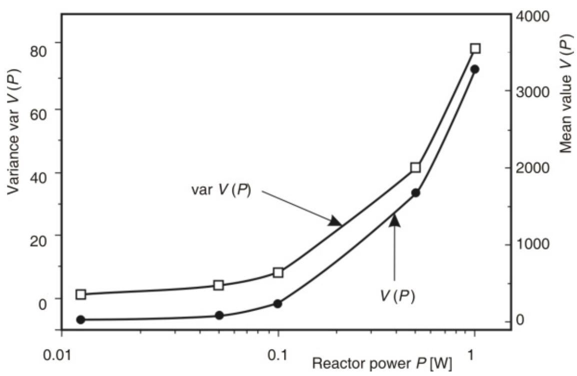

Figure 3. Determination of signal mean value and variance in stationary rating at fission power levels of 10 mW, 50 mW, 100 mW, and 1 W by using the MSV method

This implies that the mean value changes in an interval greater than two decades correspond to variance changes in intervals less than two decades. When fission power changes in an interval of two decades, successive ratios have been obtained

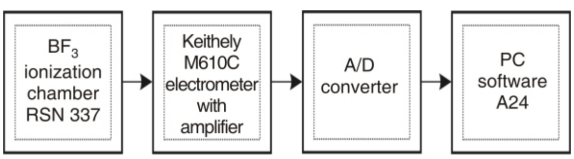

Figure 1. MSV detector signal processing system

$$\frac{V(1\,\mathrm{W})}{V(10\,\mathrm{mW})} \quad 198$$
$$\frac{\mathrm{var}\,V(1\,\mathrm{W})}{\mathrm{var}\,V(10\,\mathrm{mW})} \quad 74 \tag{5}$$

Relative changes of signal mean values and variances at an interval of fission power change from 1 W to 22 W are as follows

$$\frac{\Delta \log V}{\Delta \log \dfrac{P}{P_0}} \quad 1.12$$
$$\frac{\Delta \log(\mathrm{var}\,V)}{\Delta \log \dfrac{P}{P_0}} \quad 0.88; P_0 \quad 1\,\mathrm{W} \tag{6}$$

$$\frac{V(22\,\mathrm{W})}{V(1\,\mathrm{W})} \quad 31.3$$
$$\frac{\mathrm{var}\,V(22\,\mathrm{W})}{\mathrm{var}\,V(1\,\mathrm{W})} \quad 15.1 \tag{7}$$

The results of this measuring set are shown in figs. 4 and 5.

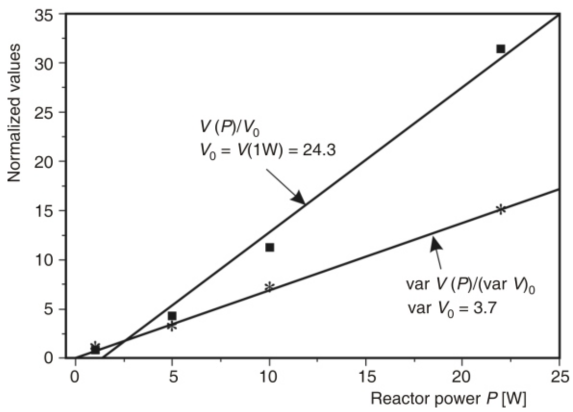

Figure 4. Determination of signal mean value and variance at interval of fission power change from 1 W to 22 W by using the standard method

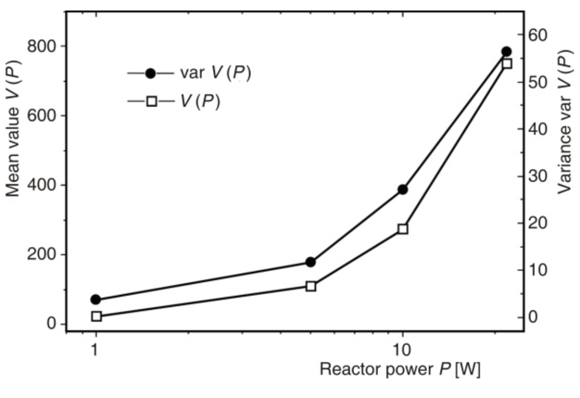

Figure 5. Determination of the signal mean value and variance at an interval of fission power change from 1 W to 22 W by using the MSV method

DISCUSSION

One of the advantages of the MSV method compared to the standard measuring method is the smaller interval of variance change against the interval of signal mean value change for the same change in reactor fission power. This property of the MSV measured chain is useful in nuclear engineering investigations in the sense that the same type of instrumentation covers the widest possible interval of reactor power change. In our experiments, during reactor power change from 10 mW to 1 W, when the signal mean value appears with a progress factor of 198, an increment in variance is defined by a progress factor of 74. A similar trend can be observed when the change in fission power is greater than one decade (1.34 decade) from 1 W to 22 W. The mean value of the signal has a larger growth (with a progress factor of 31) than signal variance growth (with a progress factor of 15). Regarding the estimated discrimination grade, we can conclude that the MSV measuring method gives fifty times greater discrimination than the classic measuring method of signal mean value.

CONCLUSIONS

In experiments in a mixed field around the RB nuclear reactor at the Vinča Institute of Nuclear Sciences, the investigation of the signal mean value change and variance change dependencies were performed within the interval of fission power change greater than one decade. The advantage of the MSV method over the classic measuring method has been ratified, because the interval of variance change is less than the interval of the mean value change for the fission power range from 10 mW to 22 W. According to our calculations, the grade of neutron-gamma discrimination is about fifty times larger with the MSV detector signal processing system. In Campbell's theory, it is well known that the most effective discrimination of the undesired signal component is realized when the momentum order of the random signal taken is high enough. It, hence, allows the realization of a measuring system of a signal momentum order greater than two. The improvement of the available MSV measured chain may also be analyzed by taking in consideration bandpass frequency, the influence of noise, response time and analysis of competitive nuclear reactions of said detection elements.

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Србољуб Ј. СТАНКОВИЋ, Братислав Д. ИРИЧАНИН, Драгана НИКОЛИЋ, Ксенија С. ЈАНКОВИЋ, Мирјана РАДЕНКОВИЋ, Ковиљка Ђ. СТАНКОВИЋ, Предраг В. ОСМОКРОВИЋ

МСВ СИСТЕМ ЗА ОБРАДУ СИГНАЛА СА НЕУТРОН-ГАМА ДИСКРИМИНАЦИЈОМ У МЕШОВИТОМ ПОЉУ

На основу принципа који су произишли из Кемпбелове теореме, у овом раду је урађена анализа неких могућности Кемпбеловог МСВ система за обраду сигнала. МСВ мод је посебно погодан за мерења која се спроводе у мешовитом пољу зрачења, када су значајно различите количине наелектрисања у детектору која потичу из интеракција два типа зрачења. Мерни детекторски елемент за мешовита n-γ поља могао би да буде одговарајућа јонизациона комора или полупроводничка компонента. Спроведено је испитивање дискриминације гама компоненте у односу на неутронску компоненту излазног сигнала из детектора, при чему су урађени прорачуни у складу са теоријским моделом интеракције зрачења са детектором. Потврђена је предност МСВ методе и закључено је да је степен n-γ дискриминације приликом МСВ обраде сигнала већа него код класичне методе мерења.

Кључне речи: неутрон-гама дискриминација, јонизациона комора, полупроводнички детектор